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Assessment of Thermal Protection Afforded by Hot Water Diving Suits

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Diver thermal comfort in cold water is presently only attainable with the use of hot water diving suits in which surface-supplied or bell-supplied hot water is flushed beneath the diver's outer protective garment over his skin or inner protective garment. An example of this suit technology (manufactured by Diving Unlimited and known as the Industrial Diver One-Piece Suit) was the subject of evaluation by DCIEM and EDU in several laboratory experiments as deep as 1400 fsw (427 msw) and in several field cold-water evaluations ranging in depth from 45 to 135 fsw (14 to 41 msw). Measurement of diver core and skin temperature as well as heat flow through the suits were made for a variety of working conditions and respiratory gas temperatures. This paper summarizes these data, showing that with proper control of inlet suit water flow and temperature, as well as heating of inspired gas, this suit technology suffices for thermal comfort for hour-long periods to depths as great as 1400 fsw (427 msw). The latter requirement is extremely important since several experiments transpired in which diver hypothermia occurred despite suit water temperatures as great as 38 C, due principally to inhalation of cold oxyhelium breathing gas.

INTRODUCTION

It is well established that cold water immersion imposes a severe hazard to diver thermoregulation due in part to the convective heat loss that it presents. Webb (1) has defined a fluid convective constant comprised of the product of the density, specific heat and thermal conductivity of the fluid divided by its viscosity. In comparison to the convective constant for air at one atmosphere and 20°C, oxyhelium hyperbaric atmospheres were many tens of times greater, even in the 450-650 fsw depth range.

Another equally important concern for diver thermoregulation is the respiratory heat loss (2) concomitant to inhalation of cold dry breathing mixtures, due to the exhalation of the inhaled gas at temperatures nearly equal to that of the body core as well as the exhalation of the gas in a totally humidified state due to evaporation from the respiratory tract. At depths below 600 fsw, this avenue of heat loss becomes of major importance to the body, exceeding convective heat loss through the diver's clothing. Even at relatively shallow depths, respiratory heat loss is of great importance in determining diver thermal strain.

Historically, the only thermal protection used in diving has been passively insulated garments of varying wet or dry designs (3). Early dry designs involved simple waterproof shells beneath which various underwear configurations were worn to provide the necessary thermal insulation. With the development of foam neoprene, this material was first used for wet suits, in which water from the environment was able to penetrate the space between the skin and the suit. With further development, this material was used in dry suit designs, beneath which improved underwear was placed. Unfortunately, whether of wet or dry design, no passive suit technology provides sustained long-term thermal comfort in cold water, even at near-surface depths (4) although recent advances in passive suit designs (5) are reported to provide thermal protection for 3-hour durations in shallow water of 3-5°C temperature. The thermal hazard is of course compounded by the respiratory heat loss increasing nearly linearly with depth.

The only suit technology that can operationally sustain diver thermal comfort is the actively-heated hot-water suit systems, principally those that are supplied with hot water via an umbilical from a surface-mounted or bell-mounted hot water heating system. Such suit systems usually consist of a loose-fitting outer shell worn over a properly-fitted inner protective wet foam neoprene suit. Hot water is circulated between the two suits from an umbilical supply line usually entering at the chest region and passing freely into the ambient environmental water from the wrist and feet seals. The suit designs permit a diver to choose the rate of water flow passing the suit. In very cold water environments, a hot-water flow rate of over 6 gallons a minute may be selected with the hot water temperature approximately 38°C (~100°F).

Although operationally successful in environments in which the divers are fairly stationary and well-supported by a surface-mounted heating system, such suits are expensive to operate, principally because of the open-circuit nature of the hot water supply. Furthermore, the diver runs the risk of occasional superficial burns by selection of an inappropriate flow rate or shortening of the umbilical supply line in the water medium (the water medium being used to reduce the hot water temperature from near-boiling values to values just below 43°C, the temperature at which skin will become burned). If the hot water supply line should be disconnected or fail in any way, the diver also may suffer from

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sudden flooding of his loose-fitting outer suit with cold water resulting in a potentially hypothermic experience. The inner suit offers some protection from this eventuality as well as the possibility of thermal injury due to high inlet water temperature. It also provides some degree of wearing comfort inside the heavy and loose-fitting outer garment.

A review of the literature showed that there was little data on the efficacy of such hot water suits at various diving depths, either in laboratory experiments or field evaluation. This paper describes the results of several such appraisals, both in the laboratory and the field.

LABORATORY EVALUATIONS

Methodology

These experiments were conducted at the Ocean Simulation Facility in Panama City, Florida, on a 1400 fsw (426.7 msw, 43.4 ATA) saturation dive conducted by the United States Navy Experimental Diving Unit. Six subjects were involved in the total of 41 man-experiments of which 32 were conducted at the bottom depth of 1400 fsw and 9 during the ensuing decompression to 1 ATA. The chamber gaseous environment consisted of 0.35-0.4 atm of oxygen with the balance comprised of helium. The experiments were conducted in water of approximately 5°C temperature and each experiment involved an exposure of 55.2 (± 23.7 standard deviation) minutes during the bottom phase of the dive and 61.3 (± 4.0) minutes during the decompression phase, during which time the divers performed little arduous activity consisting of wet pot inspection, equipment evaluation and maintenance. Not all diver activities were identical. The average duration of the total of 41 man-exposures was 56.6 (± 21.0) minutes.

Each diver wore a KMB helmet with either a gas heater built by the Naval Coastal Systems Centre or by Kinergetics as well as a hot water supplied suit, manufactured by Diving Unlimited. This surface-supplied hot water suit (similar to that known as Industrial Diver One-Piece Suit) was constructed from 6 mm (1/4 inch) neoprene foam laminated on both sides with thin nylon material. It was of open circuit design and a water-proof zipper down the front facilitated donning and doffing. The design and cut of the suit was loose-fitting to provide a space through which hot water could easily flow and, to obviate chaffing of the skin as well as to prevent localized heating and chance of minor burn, it was worn over a thin 3 mm (1/8 inch) neoprene foam close-fitting wet suit. The suits were usually supplied with hot water at a flow rate of 5 - 6 gallons per minute and a temperature of 38°C (101°F). The physical characteristics of the subjects are shown in Table I.

Each subject's body was considered as a two-compartmental system, a central core which must be maintained at 37°C for optimum physiological efficiency and a peripheral shell which was used as a physiological thermal buffer to protect the core and consequently cooled considerably in adverse cold environments. The core temperature and the mean skin temperature of each subject were continuously monitored to provide information on the relative thermal behaviour of these two compartments.

Core temperature, T_R was assessed directly with thermistor rectal probes and occasionally by radio pills (6). Mean skin temperature was measured with either 12 or 4 skin thermistors at various sites in the body by the following techniques:

(a) Hody Technique (7); A 12-site sensory measurement system with the sensors placed at the following locations:

T_1 = head,
T_2 = chest,
T_3 = rear calf,
T_4 = abdomen,
T_5 = lower arm,
T_6 = wrist,
T_7 = thigh,
T_8 = front calf,
T_9 = foot,
T_{10} = upper back,
T_{11} = lower back,
T_{12} = rear thigh.

The equation for mean skin temperature in this technique is (1)

$$\begin{aligned}\bar{T}_s = {} & 0.070T_1 + 0.085T_2 + 0.065T_3 + 0.085T_4 \\ & + 0.140T_5 + 0.050T_6 + 0.095T_7 + 0.065T_8 \\ & + 0.070T_9 + 0.090T_{10} + 0.090T_{11} + 0.095T_{12}\end{aligned}$$

(b) Ramanathan Technique (8); A 4-site sensory measurement system with sensors placed at the following locations as defined earlier: T_2, T_5, T_7 and T_8. The equation for mean skin temperature in this technique is (2)

$$\bar{T}_s = 0.3T_2 + 0.3T_5 + 0.2T_7 + 0.2T_8$$

Because of operational limitations, it was not possible in all cases to use one standard method for the assessment of mean skin temperature. In all cases, the left side of the individual diver (all right-handed) was chosen as that for sensor attachment for all sensors not on the bilateral axis of the body to reduce the amount of wear on the fragile transducer leads. Because of the tight neck seal on the various suits tested, it was necessary to affix the T_1 sensor on the left side of the neck rather than on the head.

The Hody 12-sensor technique was considered superior because of the adequate representation given to the large muscle groups and because the

TABLE I

PHYSICAL CHARACTERISTICS OF CHAMBER DIVING SUBJECTS (SIX U.S. NAVY PERSONNEL)

SUBJECT	AGE Years	HEIGHT cm	HEIGHT in	WEIGHT kg	WEIGHT lb	SURFACE AREA m^2	SURFACE AREA ft^2
WB	35	183	72	78.7	174	1.99	21.4
BH	24	175	69	79.8	176	1.94	20.9
JM	38	168	66	81.6	180	1.90	20.4
EE	32	183	72	71.2	157	1.91	20.6
CS	30	191	75	103.0	227	2.30	24.8
WS	43	175	69	71.7	158	1.86	20.0

weighting coefficients were nearly uniform, thereby reducing the error involved if one sensor read improperly or became detached from its position. With the other methods, an error in temperature assessment at any site possessing a large weighting coefficient can lead to a large error in the mean skin temperature. The fewer the sites of measurement, the greater the inaccuracy to be expected in assessment of the mean temperature.

According to this method, the mean skin temperature and the core temperature may be combined to produce a mean body temperature (MBT) via the formula:

$$MBT = 0.33\overline{T}_S + 0.67T_R \quad (3)$$

Results

The results for all 41 man-exposures in the laboratory evaluations are shown in Table II.

TABLE II

WHOLE-BODY RESULTS FOR ALL 41 CHAMBER MAN-EXPOSURES

Rectal temperature

Average change: 0.1 (±0.04 Std Dev) °C decrease
Range of measurements: -0.6 to 1.3°C

Rate of change of rectal temperature

Average: 0.002 ± 0.0065°C/minute
Range: -0.083 to 0.021°C/minute

Skin temperature

Average change: -0.66 ± 2.5°C
Range of measurements: -5.8 to 7.0°C

Range of change of skin temperature

Average: -0.014 ± 0.046°C/minute
Range: -0.14 to -0.091°C/minute

Mean body temperature

Average change: -0.16 ± 0.99°C
Range of measurements: -2.2 to +2.9°C

Rate of change of mean body temperature

Average: -0.0033 ± 0.017°C/minute
Range: -0.044 to +0.038°C/minute

Note that no significant differences were found when the results for the dives conducted during the bottom phase were compared to those conducted during saturation decompression.

All individual temperature measurements were made with thermistors accurate to within 0.1°C of the correct temperature value and all individual heat flow measurements were made with transducers accurate to within 5% of the correct heat flow value. Despite a wide range in change of rectal, mean skin and mean body temperature as well as metabolic rates, the average change over the 41 exposures was very little, with no significant change in rectal and mean body temperatures and only a one-degree decrease in mean skin temperature. A corresponding wide range of results was observed for the rate of change of rectal, mean skin and mean body temperatures. These results testify to the fact that, under proper use, the hot water-supplied diving suit technology permits diver thermoregulation within comfortable limits.

Table III shows the comparison between pre-immersion and immersion skin temperatures for the various body sites. No significant differences existed as a consequence of the immersion and hot water supply except that the neck region became colder and the wrist and lower arm became much warmer. The latter observation was presumably due to the efflux of warm water from the suit via the wrist seals. There was no significant difference seen between the dives conducted during the bottom phase as compared to the decompression phase of the experimental series.

TABLE III

AVERAGE LOCALIZED TEMPERATURES FOR CHAMBER DIVES
(All results reported in °C ± Standard Deviation)

SITE	BEFORE IMMERSION	DURING IMMERSION
T1 neck	33.7 ± 1.0 (n=7)	28.8 ± 5.1 (n=24)*
T2 chest	34.4 ± 0.5 (n=8)	34.6 ± 1.6 (n=24)
T3 rear calf	33.8 ± 0.9 (n=8)	32.8 ± 2.2 (n=24)
T4 abdomen	34.2 ± 0.5 (n=8)	34.7 ± 1.2 (n=23)
T5 lower arm	35.2 ± 0.3 (n=2)	37.3 ± 1.1 (n=10)*
T6 wrist	34.0 ± 1.3 (n=7)	37.0 ± 1.8 (n=22)*
T7 thigh	33.8 ± 0.5 (n=8)	34.3 ± 1.4 (n=24)
T8 front calf	34.3 ± 0.9 (n=8)	35.2 ± 1.6 (n=24)
T9 foot	33.3 ± 1.1 (n=7)	34.4 ± 3.0 (n=20)
T10 upper back	34.6 ± 0.3 (n=8)	34.4 ± 2.0 (n=24)
T11 lower back	34.2 ± 0.4 (n=8)	35.1 ± 1.2 (n=24)
T12 rear thigh	33.5 ± 0.4 (n=8)	33.8 ± 1.9 (n=22)

*Marked change as a consequence of hot water supply.

Note that no significant differences were found when the results for the dives conducted during the bottom phase were compared to those conducted during saturation decompression.

Figures 1 and 2 show the difference in ranking of skin temperatures at the body measurement sites (pre-dive as well as during the dive) for the dives conducted during the bottom phase as well as during the decompression phase of the experimental series. These figures show that as a consequence of diving in both the bottom and decompression phases, the neck and trunk body sites decreased in ranking. This is to be expected since the hot water flow moves from the trunk region to that of the limbs where it is released to the ambient environment through the wrist and foot seals; consequently, the large amount of flow in the limb region suffices to increase the ranking of the limb body sites. Little difference existed between the bottom and decompression phases except that the chest and back sites were lower in ranking during the bottom phase.

Despite the benefit generally afforded divers by the hot water suit technology in these experiments, it should be remembered that such benefit depended on prevention of significant respiratory heat loss by the use of gas heaters. An attempt was made to attain the inspired gas temperatures recommended by Braithwaite (9) but this was not always feasible. In two cases, the inspired gas temperature was as low as 14.5°C during the bottom phase and significant diver hypothermia resulted as shown in Figures 3 and 4. In the first and most severe case, the flow rate was only 3 gallons/minute and both the rectal and mean skin temperatures decreased precipitously as a consequence of the low flow rate and the poor performance of the respiratory heater, despite the fact that the diver did not notice any cooling or loss of body heat. In the second case, the flow rate (for the same diver) was higher and was maintained at values close to those of hyperbaric thermal neutrality throughout the dive, yet the diver still experienced substantial body core cooling, again attributable to poor respiratory gas heating. These examples demonstrate the importance of respiratory gas heating at great depths, even with the use of beneficial hot water suit technology. With a hot water flow rate greater than 6 gallons/minute and adequate respiratory heating, no diver hypothermia was observed and all divers reported experiencing thermal comfort.

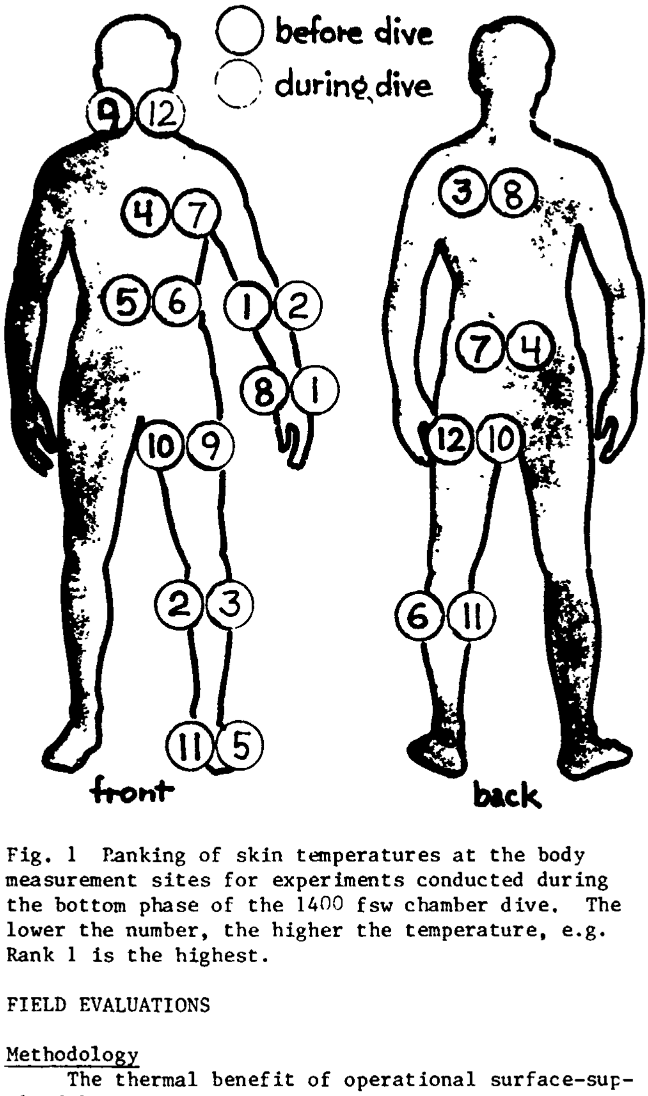

Fig. 1 Ranking of skin temperatures at the body measurement sites for experiments conducted during the bottom phase of the 1400 fsw chamber dive. The lower the number, the higher the temperature, e.g. Rank 1 is the highest.

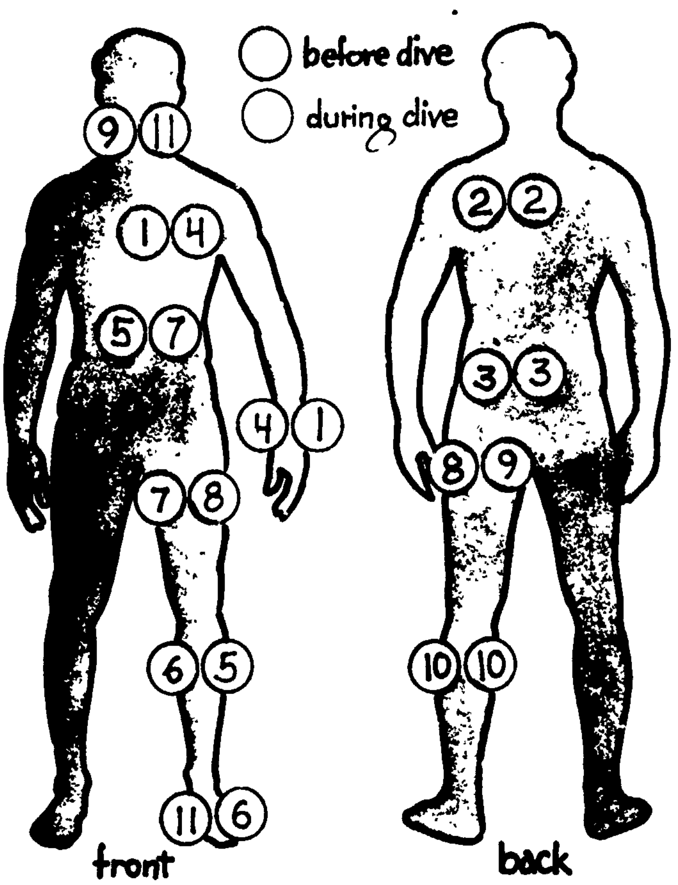

Fig. 2 Ranking of skin temperatures at the body measurement sites for experiments conducted during the decompression phase of the 1400 fsw chamber dive. The lower the number, the higher the temperature, e.g. Rank 1 is the highest.

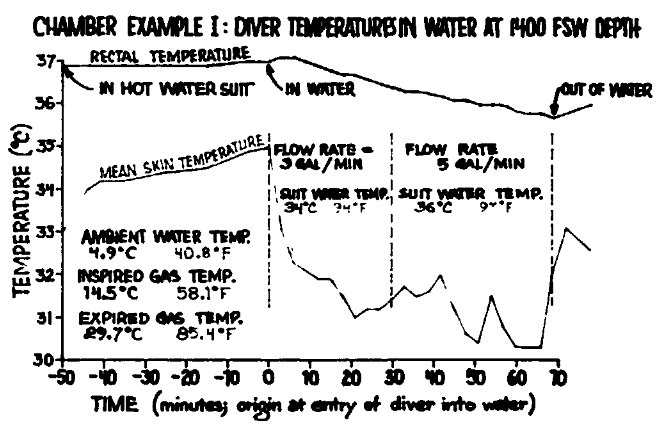

Fig. 3

FIELD EVALUATIONS

Methodology

The thermal benefit of operational surface-supplied hot water suits was assessed in open-water dives at Halifax Harbour, Nova Scotia. Eight Canadian Forces divers participated in 18 man-dives to depths of 43 msw (140 fsw) for 30-minute bottom times in water temperatures of 5°C, breathing either compressed air or 20/80 oxyhelium gas, while working during the bottom phase only on assembly of a pipe puzzle, a task that was described by all divers as "difficult and exhausting". Eleven divers wore the same hot water suit type as tested in the chamber evaluation. The rate of water flow and water temperature in the suits was the same as for the laboratory evaluations although as was the case in the earlier trials, there was no way of monitoring the amount of water dumped by a diver before it entered his suit. Seven divers wore the Yokohoma suit (10), a conventional dry suit comprised of a water-impermeable outer covering worn over several layers of nylon pile underwear. All the divers wore a Rat Hat diving helmet with a Kinergetics passive respiratory heat exchanger. Diver decompression took place in the water according to the Kidd-Stubbs decompression model (11).

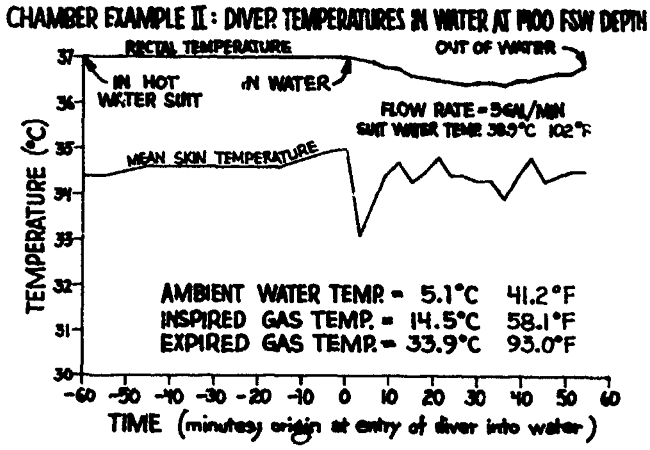

Fig. 4

Results

Since the cold exposure on these field dives was not as intense as during the laboratory evaluations, rectal temperautre changes were relatively insignificant and recourse was made to skin temperature differences in an attempt to emphasize differences in thermal response. All measurements were made with thermistors accurate to within 0.1°C of calibration temperatures.

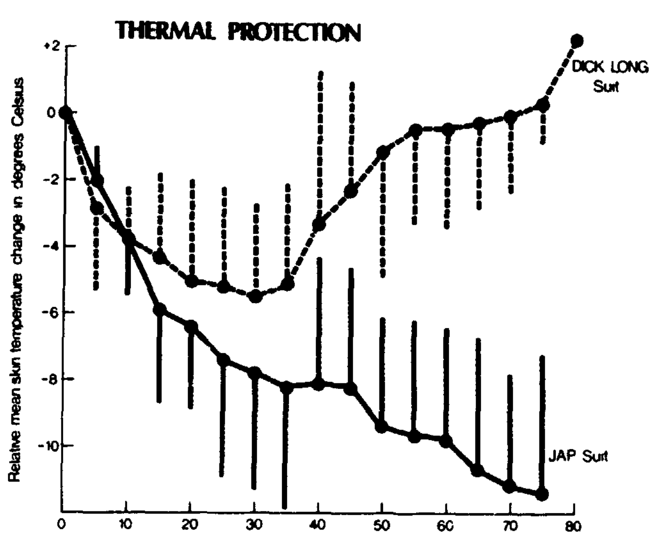

Fig. 5 Mean relative change in mean skin temperature for divers wearing the surface-supplied hot water suits and the Yokohoma dry suit (JAP suit) during dives to 43 msw. The bars indicate standard deviations from the mean readings.

Figure 5 shows the mean relative change in mean skin temperature for the divers wearing the two types of suits (each diver served as his own control and only the change in his mean skin temperature was used to compute the mean relative change). The first 30 minutes pertains to the bottom phase of the experiment and the period in excess of 30 minutes pertains to decompression in the water. Despite a trend for the Yokohoma-suited diver to be colder, there was no significant difference between the two suits in the first 30 minutes. Both types of suits did not ensure diver thermoneutrality and the divers all cooled. During decompression, the hot water-suited divers experienced skin rewarming and their mean skin temperatures returned to pre-dive values by the end of the dive, 50 minutes later. The Yokohoma-suited divers continued to cool during decompression.

Of the eleven hot water-supplied divers, six breathed 20/80 oxyhelium and five breathed compressed air during their cold water exposures. As stated previously, no significant rectal temperature changes were observed between these two groups throughout their water exposures.

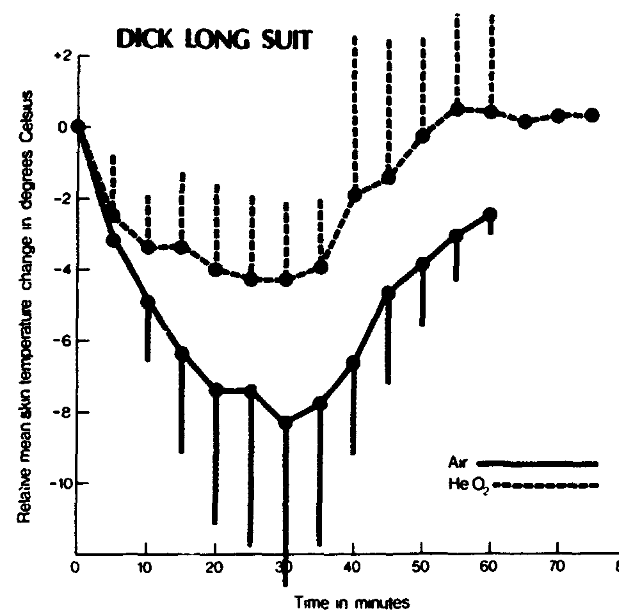

Fig. 6 Mean relative change in mean skin temperature for divers wearing the surface-supplied hot water suits for two different breathing gases, compressed air and 20/80 oxyhelium, during dives to 43 msw. The bars indicate standard deviations from the mean readings.

Figure 6 shows the mean relative change in mean skin temperature for these two groups of subjects. As shown by the combined results in Figure 5, the divers cooled during the 30-minute bottom phase and were rewarmed during the ensuing decompression in the water. Although there was no significant difference between the two groups breathing different gases, the trend of difference was that the group breathing air was cooler than that breathing oxyhelium and if the population in the two groups was greater, the difference would have become significant. The group breathing oxyhelium was expected to be colder due to the higher heat conduction and convection of this gas; the fact that this was not observed may have been due to the presumed greater efficiency of the Kinergetics passive respiratory heat exchanger with oxyhelium than with air at relatively shallow diving depths (12).

CONCLUSIONS

The proper use of hot water-supplied suits at great depths (1400 fsw) in saturation chambers was shown to be sufficient for the maintenance of diver thermal comfort and well-being as long as respiratory heat loss was carefully controlled and minimized. In such use, the only notable thermal changes were a relative improvement of the temperatures of the limbs and periphery, beneficial in the maintenance of diver dexterity. The importance of ensuring that skin temperature be kept uniform and that mean skin temperature and inspired gas temperatures be kept near 35°C has also recently been emphasized in experiments on hot water suited divers conducted at 130-145 msw in the North Sea (13).

Although beneficial to diver heating in the field experiments, the provision of thermal comfort was not as satisfactory as for the laboratory evaluations and the divers experienced peripheral body cooling during the bottom phase of the relatively shallow (140 fsw) depths, presumably because of the greater difficulty in ensuring a continuous and safe flow of warm water to the divers from a barge in a working environment. During the diver decompression in the cold water there was a return to thermoneutrality conditions because of the greater efficiency of hot water delivery at shallow depths. There was some indication that the efficient use of a passive heat exchanger would provide a slightly greater respiratory heat saving for oxyhelium as compared to the compressed air.

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